Simulating weathering of basalt on Mars and Earth by thermal cycling

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[1] Physical weathering induced by heating and cooling may cause rock breakdown on Mars and Earth. We report results from parallel weathering simulations on basalt blocks exposed to diurnal cycles representing Mars-like (two simulation runs from −55 to +20 °C and −75 to +10 °C, 1–100% relative humidity, 4–8 mbar pressure, CO_2 atmosphere) and hot arid Earth (23–72° C, 30–100% relative humidity) conditions. Under Earth conditions, thermally pre-stressed blocks showed measurable strength declines, whilst salt pre-treated blocks showed strength gains. Under Mars-like conditions, pre-stressed blocks recorded greater or similar strength declines and salt pre-treated blocks showed more muted strength declines than under Earth conditions. The results imply that on Earth and Mars diurnal cycling of temperature alone can cause deterioration of basalt with a pre-existing stress history. The type of stress history is important, with salt pre-treatment affecting the response of thermally pre-stressed blocks under both Earth and Mars conditions.
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1. Introduction

[2] Physical weathering plays a key role in rock breakdown and landscape development and constrains chemical weathering rates by controlling the production of weatherable material. On Earth physical weathering related to thermal cycling may be a crucial component of rock breakdown in arid landscapes. Since the early work of *Blackwelder* [1933] there has been debate over whether thermal stresses from insolation are sufficient to produce physical weathering and whether moisture is needed to induce breakdown. *Richter and Simmons* [1974] found experimentally that heating igneous rocks at rates >2°C/minute or maximum temperatures >350°C was required to produce permanent strain and generate cracks. These thresholds have become entrenched dogma in much geomorphological literature, but little evidence has been collected to test them. Observations of preferential azimuthal orientation of cracks on boulders suggest a role for solar-thermal weathering in desert environments even though these thresholds are not exceeded [*McFadden et al.*, 2005]. The synergistic or confounding influences of other factors such as moisture and salts on thermal weathering have been suggested by field observations but not yet systematically investigated [*Moores et al.*, 2008].

[3] For Mars, since the pioneering work of *Malin* [1974], there has been recognition that physical weathering might have produced some of the breakdown features captured by lander and rover imagery [e.g., *Rodriguez-Navarro*, 1998; *Chan et al.*, 2008]. Furthermore, modelling and terrestrial field data indicate that thermal stresses from rapid changes in the receipt of solar energy might alone be sufficient to produce physical weathering under present day Mars conditions [*Leask and Wilson*, 2003; *McFadden et al.*, 2005]. However, to date there have been no experimental tests of physical weathering processes under current Martian conditions to ascertain whether thermal cycling is likely to produce rock breakdown. Understanding the past and present efficacy of physical weathering of basalt is a key question for interpreting present-day landscapes on Mars and one which we address here through laboratory simulations.

2. Experimental Design

[4] A fine-grained, dense, olivine-bearing basalt with plagioclase phenocrysts from China (cf. basalt from Gusev crater found in the work by *McSween et al.* [2006]) was cut into 9 cm x 2.5 cm x 2.1 cm blocks and treated to create four sample groups with distinct weathering "histories"; (Group 1) baseline, no salt; (Group 2) baseline, salt-treated; (Group 3) thermally pre-stressed, no salt; and (Group 4) thermally pre-stressed and then salt-treated. The baseline condition represents situations found in nature when a relatively pristine, unaltered rock is exposed at the surface, whilst the pre-stressed condition simulates a rock with an existing thermal emplacement or surface weathering history (e.g., from thermal cycling, unloading, impact). In order to rapidly impose such history pre-stressed blocks were subjected to five cycles of heating to 300°C then quenched in water to produce microfractures comparable to those produced by long-term surface weathering [*Warke*, 2007]. Pre-stressing caused 30–40% reduction in compressive strength. In order to simulate the likely condition in many arid environments (including Mars) where rocks are affected by salts, we subjected some blocks to salt treatment by oven-drying them and then immersing them in saturated $NaSO_4$ solution for 48 hours to allow salt penetration [*Goudie*, 1993]. Sulfate salts are known to be abundant in both terrestrial deserts [*Goudie and Viles*,

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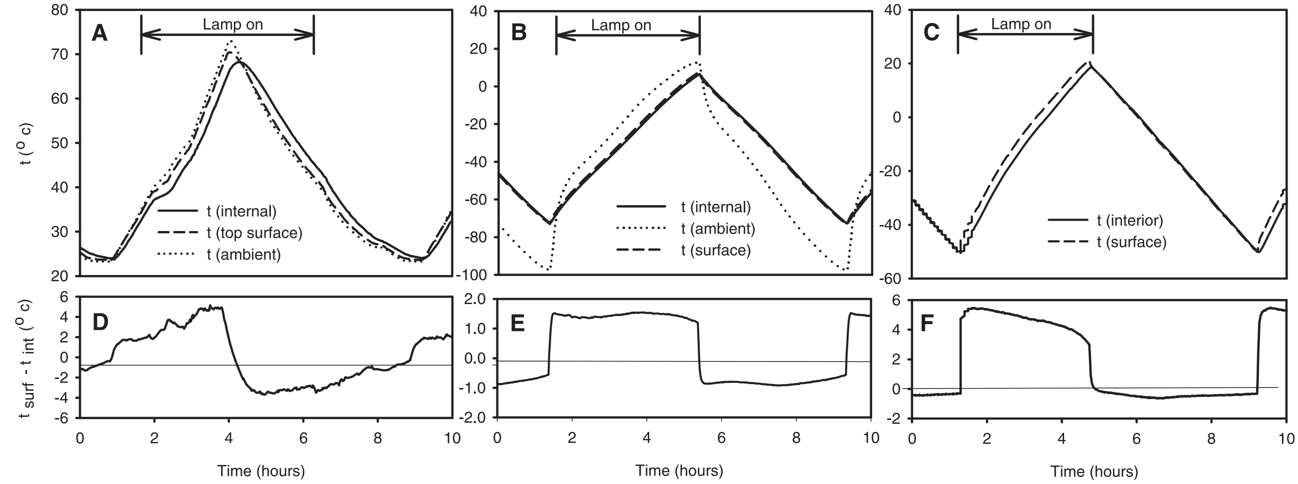

Figure 1. Temperature cycling of air, block top surface and block interior experienced in (a) Earth simulation chamber and (b and c) Mars simulation chamber. Temperature differentials between basalt block surface and interior (depth = 1cm) for (d) Earth and (e and f) Mars simulations.

1997] and Mars surface soils [*Wang et al.*, 2006]. $NaSO_4$ was chosen rather than an iron or magnesium sulfate typical for Mars since it is known to promote aggressive weathering [*Goudie and Viles*, 1997] and was likely to produce effects during the relatively short time period available for this study. Salt treatment was found to affect thermally pre-stressed blocks differently. For blocks from Group 2, salts precipitated circularly around a nucleation point while Group 4 blocks showed veined salts in microfractures created during pre-stressing. Such pre-treatment regimes impose a known stress history on samples, which reflect, but cannot mimic, natural stress histories. The small block size was chosen to fit a sufficient number of sample replicates in the Mars weathering chamber and to obtain a length:width ratio ≥ 3:1, required for assessment of elastic strength.

[5] For the terrestrial physical weathering simulation, a Fisons FE300 environmental cabinet was used to cycle air temperature (23°C to 72°C) and relative humidity (100% to 30%) as in Figure 1a, based on a composite of recorded diurnal cycles from Wadi Digla, Egypt and the Negev Desert, Israel [*Goudie and Viles*, 1997]. For the Mars physical weathering simulation, a sealed chamber was constructed to contain the samples in an atmosphere of carbon dioxide, which was slowly pumped down to a pressure of 6 ± 2 mbar. To ensure rapid heating and cooling of the sample chamber, it was constructed out of aluminium (high thermal conductivity), and placed inside an outer vacuum chamber for thermal isolation from the environment (Figure 2a). Temperatures within the chamber were controlled, using a closed-cycle cooler, so that rock surface

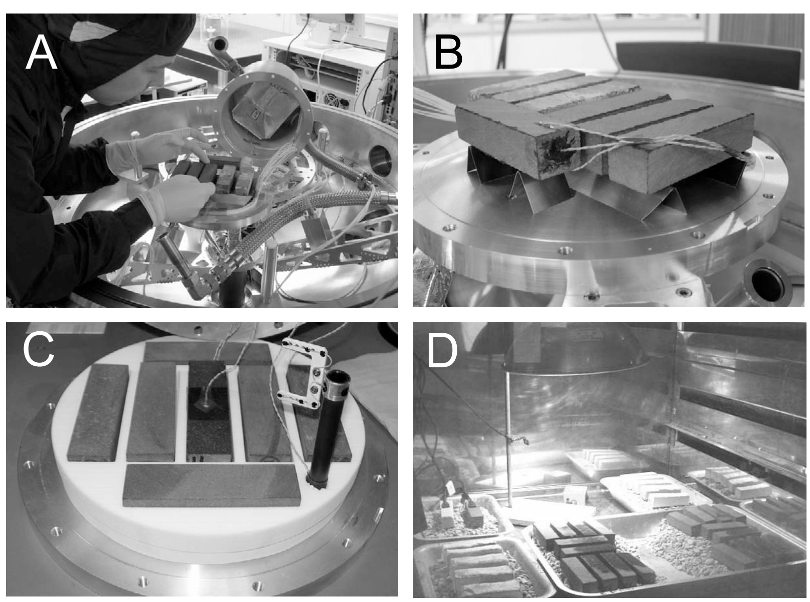

Figure 2. (a) Mars simulation chamber with lamp at the top. (b) Placement of test blocks and instrumented block within Mars simulation chamber on triangular stands Mars run A. (c) Placement of test and instrumented blocks and Rohacell foam in Mars run B. (d) The Earth simulation chamber showing dew on basalt blocks in centre.

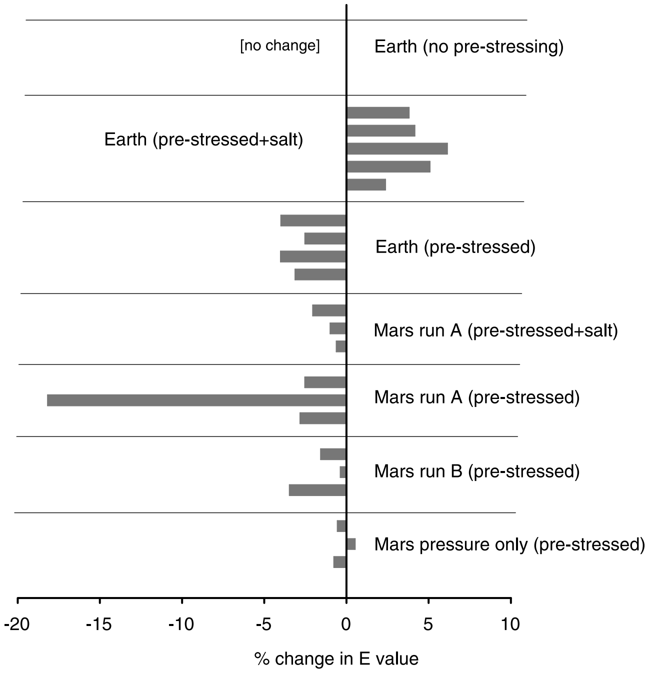

Figure 3. Changes in elastic modulus after 36 temperature cycles under Earth and Mars-like (run A and run B) conditions, and after 12 air pressure cycles for baseline, pre-stressed and salt-treated blocks.

temperatures cycled between −75°C and 10°C (run A, Figure 1b) and −55 °C and 20 °C (run B, Figure 1c), comparable to those derived for Mars summertime conditions [*Spanovich et al.*, 2006]. We note that this temperature range is greater than that expected for a large area of exposed bedrock due to its high thermal inertia [see, e.g., *Fergason et al.*, 2006], but is consistent with a small basalt rock surrounded by a dusty region with low thermal inertia.

[6] A lamp in each cabinet provided direct heating of rock surfaces by radiation in addition to heat transfer from convection and conduction of air. This closely mimics natural conditions of heat transfer [*Warke and Smith*, 1998]. In the Mars chamber, a halogen incandescent bulb was placed 20 cm from the samples, dissipating 12W of power. In the Earth chamber a 40W bulb was placed approximately 40 cm above the samples, producing realistic radiant heating of the block surfaces. To minimize chamber time, a 24 hour diurnal cycle was compressed to 8 hours by reducing the amount of time at near constant temperatures, while maintaining approximately the same rate change of temperature during periods of maximum heating and cooling (~0.3°C/min for both simulations).

[7] Thirty six cycles were run in both chambers. All four block sample groups were tested in the Earth weathering simulation while only the stressed cases, (Group 3 and Group 4), were assessed in Mars weathering simulation run A due to the small size of the sample chamber. Mars simulation run B utilised only Group 3 samples. Blocks were placed on a gravel bed in the Earth chamber and on 15mm triangular stands in the Mars chamber so as to isolate the blocks from the chamber base in run A (Figure 2b). In Mars run B blocks were semi-embedded in a Rohacell foam (thermal inertia c. 40 J m^{-2} J^{-1} $s^{-0.5}$, comparable to Mars sediment surface values of 100–200 J m^{-2} J^{-1} $s^{-0.5}$ by *Fergason et al.* [2006] (Figure 2c) in order to better recreate Mars-like thermal gradients.

[8] The initial stages of weathering were recorded by monitoring the changing elastic strength of the samples using an MK5 Grindosonic apparatus, which measures the frequency of the resonant flexural vibration mode (R value) from which elastic modulus (E) values (in GPa) are calculated. The technique is non-destructive and E values are linearly related to compressive strength [*Allison*, 1990]. Measurements were made every 6 cycles in the terrestrial simulation and the beginning and end of the Mars simulations. Thin sections and SEM samples from pre- and post-trial blocks were also examined to search for incipient breakdown (e.g., micro-fractures) which might explain any observed strength changes.

3. Results

[9] Figure 1 indicates that our experimental design successfully reproduced air and rock temperature fluctuations known for hot desert conditions on Earth [*Warke and Smith*, 1998] and for Mars [*Spanovich et al.*, 2006]. Use of the insulating foam in Mars run B resulted in higher thermal gradients between the top and middle of the block than those recorded in run A (Figures 1e and 1f). In the Wadi Digla/Negev simulation, dew was observed to precipitate on the top surface of the blocks during low temperature, high relative humidity night-time conditions and salts were clearly mobilized (Figure 2d). Differences in the block internal versus surface temperature in Figures 1d–1f result from contrasting contributions of radiant and convective heating to thermal cycling regimes in Mars versus Earth chambers. Relative humidity in the Mars chamber was estimated to be c. 1% at the maximum of the temperature cycle, and saturated for the colder portions of the cycle, representative of Mars conditions [*Hudson et al.*, 2009].

[10] Figure 3 illustrates that, for the Earth simulation, the pre-stressed and salt-treated blocks responded differently to those that were pre-stressed only, with the former becoming apparently stronger over the course of the experiment, and the latter weaker. Basalt blocks with no pre-stressing recorded no strength change. Thin sections cut from a range of blocks subjected to both simulations and controls showed no obvious physical causes of the strength changes. However, SEM counts of cracks >50 μm width and length within 2 mm^2 areas from the surface and the interior of one block from each sample group revealed more cracks in groups 3 and 4 (4 and 9 cracks) vs. 1 and 2 (0 and 1 crack). It is impossible to determine how many of these were generated prior to the weathering simulation, but the greatest number of near-surface cracks is found in blocks that experienced measurable strength decrease.

[11] Figure 3 indicates that the samples from the two Mars simulation runs showed both similar and different behaviour to those in the Earth simulation. For blocks that were pre-stressed only, declines in strength were comparable to or greater than in the Earth simulation. One block showed a considerable reduction in strength. In contrast, blocks pre-treated with salt and subjected to run A conditions did not record the strength increase observed during the Earth simulation. However, the loss in strength was smaller than that experienced by the pre-stressed (no salt) blocks in run

A, suggesting that salt may play a role in retarding deterioration even under Mars-like conditions.

[12] Test blocks exposed to twelve pressure cycles between 1 atm and 7 mbar showed no decline in strength, suggesting that any recorded strength changes in the Mars case are a result of the thermal cycling rather than atmospheric pressure cycling.

4. Discussion and Conclusions

[13] The decline in strength measured for the pre-stressed blocks under the Earth simulation demonstrates that temperature and relative humidity cycling representative of hot desert conditions can cause deterioration of basalt without any contribution from salt weathering or other processes. Sample blocks not subjected to experimental pre-stressing experienced no strength declines, implying that typical terrestrial desert temperatures may be insufficient to instigate new cracking, at least in unconfined rocks. Similar strength loss (as measured by ultrasonic pulse velocity changes) was also noted in pre-stressed basalt blocks exposed in Death Valley, USA for two years [*Warke*, 2007]. Our results may be conservative, as *McFadden et al.* [2005] note larger blocks experience larger temperature gradients and stresses. Our pre-stressing regime caused a near-surface network of cracks, apparently enhanced by the subsequent experimental thermal cycles that are likely the cause of decreased strength values. Whilst the way we produced these cracks does not exactly mimic real stress histories, such micro-fractures have been observed in boulders on Earth subjected to a range of process regimes (e.g., fluvial transport [*Ehlmann et al.*, 2008]) and are likely also to occur on Mars where stresses due to aeolian, temperature and meteorite impact are common. These findings suggest that relatively moderate rates of temperature change (~0.3 °C/min in these experiments) can induce breakdown in rocks with a stress history (i.e., most natural rocks) and the oft-quoted 2°C/minute temperature change rate is not necessary to induce strength loss by thermal cycling.

[14] Transient strength increases similar to those noted on the pre-stressed and salt-treated blocks have been recorded from other salt weathering simulations [*Zhu et al.*, 2003] and for granite blocks exposed in the coastal Namib Desert for 2 years [*Viles and Goudie*, 2007]. However, if we had run our Earth simulation for longer we propose that weakening of the salted blocks would occur, as the initial cementing role of salts is replaced by a deteriorative role. Examination of the blocks after the pre-stressing and subsequent salt treatment showed that salt became preferentially deposited within the network of surface cracks produced by the pre-stressing. Thus, salt dissolution, mobilization, and crystallization cycles initiated by periodic water condensation on rock surfaces are likely to be focused within these superficial cracks and would, over time, be expected to enhance them.

[15] Blocks from the Mars simulation showed declines in strength similar to those of the Earth simulation, despite the different atmospheric conditions. This shows that diurnal cycling of temperatures on Mars can cause deterioration of rocks with a pre-existing stress history, as would be typical for surface rocks here. The >10% strength decline for one sample implies that dramatic failures of basalt boulders could occur under current Martian conditions, apparently due only to thermal cycling. Although we could not track sample elastic modulus values throughout the entire experiment as in the terrestrial case, salt did not appear to play the same role as an initial cementing agent under the present day Mars conditions simulated in the chamber. The lack of liquid water likely accounts for this difference, i.e., there was no cyclic salt dissolution and reprecipitation nor appreciable dehydration and rehydration under the relative humidity conditions simulated. The slightly more muted decline in strength experienced by the pre-stressed blocks treated with salt relative to the unsalted blocks in the Mars simulation (run A) is hard to explain, but illustrates that even under highly dry conditions, salts complicate the response of basalt blocks to temperature cycling.

[16] Importantly, even in the short length of time simulated by this study, measurable, albeit slight (~1%), weakening was recorded for basalt blocks under present Mars surface conditions using two variant run conditions. Extrapolation of experimental results simulating a month of diurnal change to millions of years of geologic time is necessarily suspect. Surfaces may reach equilibrium with their surroundings and little additional weathering may occur after initial weakening. However, our results imply firstly, the surface of Mars today is potentially an active physical weathering environment comparable to that found in Earth deserts and secondly, it is unlikely that the present landscape of boulders and outcrops is fully representative of morphology during the time of deposition millions or billions of years ago. While a 1 nm/yr average erosion rate is often cited for the Mars surface [e.g., *Golombek et al.*, 2006], the susceptibility of basalt rocks to thermal stresses and the likelihood of additional processes like salt weathering in the recent Mars past suggest that rocks in the present landscape have been substantially modified and that production (by thermal physical weathering) of fresh debris available for chemical weathering is an ongoing process.

[17] In conclusion, our study is the first to directly simulate physical weathering in the present Mars environment and compare it with Earth simulations. Our Mars simulation chamber provided realistic temperature regimes in the experimental blocks. We find that physical weakening of pre-stressed basalt occurs under accelerated diurnal cycles alone with ~0.3 °C/min temperature change even in extremely dry conditions and that salts influence the response of basalts to thermal weathering.

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